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THE WAVE PROPERTIES OF ELECTRONS

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A RÉSUMÉ
OF THE PRESENT STATE OF KNOWLEDGE REGARDING
THE PROPERTIES OF ELECTRONS WITH SPECIAL REFERENCE
TO THEIR NEWLY-DISCOVERED WAVE PROPERTIES

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THE WAVE PROPERTIES OF ELECTRONS

By C. J. DAVISSON

IN AN essay published in a recent issue of the *Proceedings* our president has explained to us the nature of thought, and has pointed out its limitations. The circumstance which prompted Dr. Dercum to undertake the exposition of these interesting matters is the difficulty experienced in physics at the present time in forming tangible conceptions of certain processes and certain relationships which have been discovered since the beginning of this century—in particular, the difficulty in forming any mental picture of the so-called quantum processes or of visualizing electrons which behave in some circumstances as particles and in others as waves.

If I follow Dr. Dercum, these difficulties in comprehension arise from limitations imposed upon our thinking processes by the nature of our neural protoplasm. If we were equipped with a better kind of protoplasm, one more completely responsive to stimulations by our environment, and capable of a more varied reaction to these stimulations, our comprehension of our environment would be, or at any rate could be, more complete. Things which are incomprehensible to us with our present equipment would in these imagined conditions present fewer difficulties. An individual who has been blind and deaf since birth is capable necessarily of a less complete appreciation and comprehension of his environment than one with normal sight and hearing. And yet the individual with normal sight and hearing is, as we know, blind and deaf to great ranges of light and sound frequencies. It is conceivable even that other forms of stimulation exist in his environment for which he has evolved no receptors whatever.

[1] Francis X. Dercum, "On the Nature of Thought and Its Limitations," *Proc. Am. Phil. Soc.*, LXVIII, 4, 275 (1929).

His conception of his environment and of the processes going on within it is, therefore, imperfect and incomplete and must forever remain so. This, as I understand it, is Dr. Dercum's thesis, and it is, I think, a comforting one as it offers us a legitimate excuse for giving our neural protoplasm a much needed rest. If elements in our environment are, in the nature of the case, incomprehensible to us, it is certainly foolish of us to waste time trying to comprehend them. The difficulty in pursuing this policy is no doubt that we have no test for distinguishing, a priori, the comprehensible from the incomprehensible.

It is not my purpose to discuss this fascinating subject, but to explain to you, as well as I can, one of the circumstances to which it owes its present interest: namely, the duality of apparently irreconcilable wave and corpuscular properties which characterizes electrons. This matter has not, I think, been presented previously to the Society. Before speaking of the newly discovered wave properties of electrons, I shall remind you briefly of some of the compelling reasons we have for regarding electrons as particles. It is important to do this in order that you may appreciate more fully the difficulty involved in regarding them at the same time as waves.

It was discovered more than thirty years ago that the many varied and often beautiful phenomena which are observed in highly exhausted electrical discharge tubes—Geissler tubes, Crookes tubes, Roentgen ray tubes, and the like—are due primarily to a radiation proceeding from the cathodes of these devices. It was revealed in experiments made by J. J. Thomson in England and by Wiechert in Germany in the closing years of the last century that beams of this radiation are deflected in electric and magnetic fields, in just the manner in which we should expect them to be deflected if the radiation were a stream of swiftly moving negatively charged particles. It was found possible in fact to calculate from measurements of these deflections and other data the velocities of these hypothetical particles, and also the ratio of their electrical charge to their mass. The value found for this ratio was much

greater than the largest displayed by any kind of electrolytic ion, and from this it was inferred that the particles are much lighter than the lightest atoms. This evidence of the existence of a subatomic particle of definite charge and mass was readily accepted not only because the evidence was in itself convincing but also because the idea was not a new one. The existence of an ultimate unit of electric charge had already been inferred from Faraday's Laws of Electrolysis, and the word "electron" had already been coined to designate this atom of electricity. Also, Lorentz, in attempting to explain the then recently discovered Zeeman effect, had formulated a partially successful theory in which it was assumed that particles of definite charge and mass exist within the atom. The value which had to be assigned to the charge-to-mass ratio of these, in order to obtain agreement of his theory with Zeeman's observations, was the same as that found by Thomson and Wiechert in their more direct experiments.

During twenty-five years of intensive experimentation which followed upon the work of Thomson and Wiechert, this conception of the electron as a subatomic negatively charged particle was repeatedly justified and confirmed by experiments of the most diversified kinds. Electrons were found to be a universal constituent of matter. They could be abstracted from any kind of matter in a variety of ways. They could be vaporized from matter by heating; they streamed forth under the solicitation of light and x-rays; they were ejected spontaneously by radioactive materials. Measurements were made of their charge, most precisely in the famous oil drop experiments of Millikan. By combining this result with the most reliable determinations of the charge to mass ratio, one could write down a value for the mass of the electron correct probably to within a few parts in a thousand. Estimates could be made of its linear dimensions on the assumption that its mass was entirely electromagnetic. If any doubt had existed regarding the corpuscular nature of electrons, it must have been dispelled by the beautiful experiments of C. T. R. Wilson in which the tracks pursued by individual

electrons in traversing a gas are rendered visible. The discreteness of electrons is further attested by the fluctuations which are observed in the current flowing from a heated filament; these are of just the character and magnitude to be expected for the random emission of charges of the known magnitude of electrons.

The corpuscular nature of electronic radiations had been verified in what seemed every conceivable way. The conception seemed adequate and sufficient for all demands which might be made upon it. An elaborate theory based upon this conception of the electron had been built up to explain the optical and electrical properties of matter—and this conception was fundamental also to the famous theory of the atom devised by Bohr. It cannot be said, however, that this electron theory of matter was uniformly successful in all of its ramifications. It was, in fact, the deficiencies of this theory together with certain new conceptions from the field of optics which led Louis de Broglie to suggest about five years ago that the conception of the electron as a particle might in certain circumstances be found inadequate. The circumstances contemplated were those in which the system under consideration is one of atomic dimensions. It was de Broglie's idea that in cases of this kind certain waves which he conceived of as associated with electrons might be expected to manifest themselves. The conception grew out of the reverse situation in optics in which light had come to be recognized as having corpuscular as well as wave properties, out of the mysterious correlation of frequency and energy which we meet with in quantum phenomena, and out of the correlation of mass and energy which appears in the theory of relativity. These were the antecedents of de Broglie's idea, and yet in the last analysis the idea was arrived at by a brilliant leap of the imagination.

It has been immensely fruitful. It has led to a new and remarkably successful conception of the atom from which the corpuscular electron as an essential feature has altogether disappeared. The planetary system of electrons conceived by

Bohr is replaced by a medium continuous though inhomogeneous, capable of natural vibrations. The fact that these vibrations take place in general in a space of more dimensions than three, and that we have as yet no idea what it is that vibrates, makes visualization of atomic processes a discouraging enterprise, and yet this is less disturbing to the theoretical physicist than might be supposed. He has outgrown the ambition of Lord Kelvin; he no longer tries to devise a mechanical model of every phenomenon. It has been discovered in fact, that a certain æsthetic pleasure is derived from dealing in calculations with symbols which evoke no mental pictures whatever.

De Broglie's idea has been invaluable not only as the basis of a new theory of the atom, but also as the basis of an entirely new theory of mechanics. And in these developments de Broglie has been himself a leader. In its turn the new mechanical theory has suggested experiments by which the wave-like aspects of electrons might be demonstrated. Many of these experiments have now been made; it is of a few of them that I wish particularly to speak. The simplest of all is the experiment by which it is demonstrated that electrons are regularly or "specularly" reflected from the surface of a crystal. We find when a stream of electrons is directed against the face of a crystal that some of the incident particles return from it without loss of energy, and that most of these recede from the crystal face in the direction of regular reflection. The observation is illustrated in Fig. 1. The incident electrons approach the crystal in this particular case along a direction which makes an angle of 38 degrees with the normal to its surface. The curve on the right indicates the way in which the electrons scattered without loss of energy are distributed in direction; most of them depart in a direction lying in the plane of incidence and making with the normal to the crystal face the same angle as the incident beam. There is a strong and well defined beam of regularly reflected electrons. This phenomenon cannot be explained in terms of atoms and electrons as previously conceived.

Picture the crystal built up of atoms, each of them enormous in size compared to an electron and each of them comprising a nucleus surrounded by a large number of electrons rotating in closed orbits. Imagine now an electron plunging into this galaxy of planetary systems. It is obviously a comet. The simplest event which may ensue will be a cometwise deflection of the electron in the field of some atom into which it happens to strike, and then a speeding away of the electron from the crystal without loss of energy. The direction taken by the departing electron will be determined by a number of circumstances, one of which will be the distance

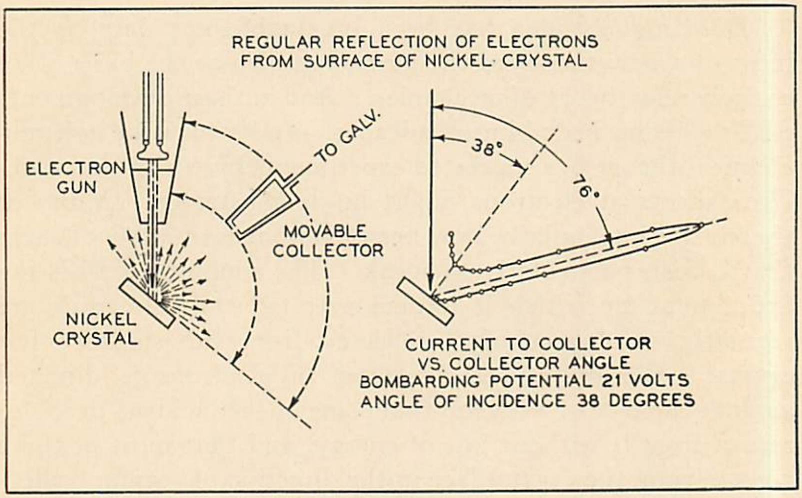

Fig. 1

from its line of approach to the nucleus of the atom responsible for its deflection. This distance will be different for different electrons—and as a consequence electrons will be scattered more or less uniformly in all directions. This is the picture of electrons scattering in terms of Bohr atoms and purely corpuscular electrons, and it is quite inadequate to explain the strong beam of electrons which is observed leaving the crystal in the direction of regular reflection. This is a direction related to the plane of the crystal surface. Three atoms at least are required to fix this plane which means that the

incident electron has its direction of departure determined not by one atom alone but by three atoms at least. On the older view we should have to suppose that the incident electron in some way takes account of the positions of not fewer than three atoms, and from characteristics of the reflection which I shall mention later we should have to suppose the actual number to be much greater—fifty or a hundred at least.

If on the other hand we regard the incident beam as a beam of waves instead of as a stream of particles, the regular reflection is readily explained; each wavefront of the beam comes in contact with all the atoms, and the regular reflection results, as in the case of x-rays, from constructive interference among the coherent secondary wave trains proceeding from the regularly arranged atoms of the crystal. Moreover, this view of the phenomenon enables us to understand the characteristics of the reflection to which I have already alluded—namely, the way in which the intensity of the reflected beam varies with the speed of the electrons and their angle of incidence.

The regular reflection of electrons from crystal surfaces is sufficient to establish the convenience of the conception that electrons are waves. The usefulness of the conception is not, however, limited to this particular phenomenon. There are many ways of demonstrating that x-rays are waves—or perhaps we should say, of demonstrating the convenience of the conception that x-rays are waves. Nearly all of these demonstrations have now been made also with electrons. These include the analogues of the Laue diffraction of heterogeneous waves by a single crystal, of the Hull, Debye-Scherrer diffraction of monochromatic waves by crystal aggregates, and of the diffraction of monochromatic waves by ruled gratings and narrow slits. The data of these experiments are available for the calculation of electron wavelengths, and these have the values predicted by de Broglie—a stream of electrons, each of momentum p, behaves in these diffraction experiments as a beam of waves of wavelength inversely proportional to p, the factor of proportionality being the Planckian constant h.

To further illustrate these newly discovered properties of electrons I shall show you lantern slides of two very beautiful diffraction patterns produced recently by Drs. Eisenhut and Kaupp in the laboratory of the I. G. Farbenindustrie at Ludwigshafen in Germany. The first of these was obtained by directing a beam of high speed electrons through a thin film of silver, and intercepting the transmitted electrons by a photographic plate. The film is an aggregate of tiny crystals of random orientation and the pattern of rings which appears on the plate (Fig. 2) is just the pattern which is calculated

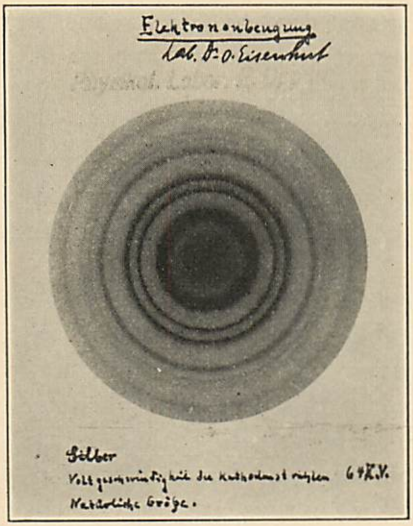

FIG. 2

from the crystal structure of silver and the assumption that the incident beam is a beam of monochromatic waves. The wavelength of the waves may be calculated from the data of the experiment and compared with the theoretical wavelength calculated from the momentum of the electrons by means of de Broglie's formula. The agreement, as has been found in all such cases, is within the limits of accuracy of the measurement. Diffraction patterns of this kind were first produced with electrons by G. P. Thomson of the University of Aberdeen.

The second pattern I shall show you is by the same investigators, and is for electrons of the same speed. The difference is that the diffracting material is, in this case, a thin lamina of mica. (Fig. 3.) Patterns of this type were pro-

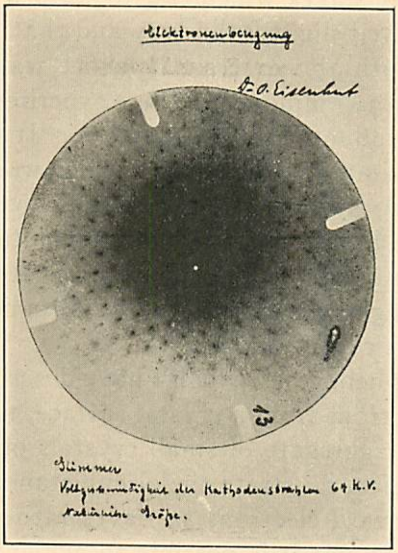

FIG. 3

duced first by Kikuchi in Japan, and for some time there was no satisfactory explanation of them. The diffracting system is a single crystal; the electrons are homogeneous in speed, the waves are monochromatic. Now it is well known to those familiar with the theory of x-ray diffraction that in general no pattern is produced when a beam of monochromatic waves traverses a single stationary crystal. One or two diffraction beams may possibly appear, but if so the event will be fortuitous; in general no beams will be observed other than the directly transmitted primary beam. Kikuchi should have known better than to make this experiment, but he did make it, and this pattern by Drs. Eisenhut and Kaupp is a beautiful example of the result he obtained. What appears to be the correct explanation of the production of this pattern has been given us recently by W. L. Bragg in England and

independently by S. B. Hendricks in Washington. Bragg and Hendricks assume that the mica crystal is to a certain extent a crystal aggregate—not an aggregate of crystals oriented at random as in the case of the film of silver, but an aggregate of tiny flakes which fail to form a perfect crystal only by being tilted slightly this way and that. This assumption together with the excessively short wavelength of the high speed electrons employed in these experiments is sufficient to explain the production of this pattern. It turns out to be, to a close approximation, the pattern which would be produced if the diffracting systems were a single layer of molecules instead of some hundreds of layers as it actually is. These patterns also are available for calculating electron wavelengths and again the agreement with the de Broglie formula is as nearly perfect as can be expected.

These three phenomena which I have described, the regular reflection of electrons from a crystal surface, the diffraction of electrons by an aggregate of small crystals of silver, and the diffraction by mica, illustrate the circumstances in which it is convenient to regard electrons as waves rather than as particles. Whether or not it is possible to achieve a unified conception of electrons in which these newly discovered wave properties appear consistent with their longer known corpuscular properties, or whether such an achievement is beyond the limits of thought is a question which does not worry the experimental physicist a great deal. It used to be said that a physicist regards light as a wave phenomenon on Mondays, Wednesdays, and Fridays, and as a corpuscular phenomenon on the other days of the week. This statement must now be extended to include electrons, and modified, I think, to state that he regards light and electrons as both waves and particles on all days of the week. And it might be added that familiarity with this idea is dulling his sense to its paradoxical nature.

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